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Problems in the Aging of Skeletal Juveniles: Perspectives From Maturation Assessments of Living Children

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ABSTRACT We employ samples of children of known chronological age to demonstrate the significance of random and systematic effects on maturation in both dental and skeletal development. Differences between chronological age for dental age in young healthy Canadian children can be as much as 100% of the actual age of the children. For skeletal development by reference to Greulich-Pyle standards, three samples of known-age children from Mexico document parallel effects: 1) 183 six-year-old children have skeletal-based ages with a 95% confidence interval of 4–8 years; 2) 80% of 217 4.0–4.5-year-old children are underaged by 1–3 years; and 3) 130 children of skeletal age between 39 and 44 months are actually between 4 and 7.4 chronological years of age. The Mexican samples are drawn from a population living under conditions of environmental stress with chronic mild to moderate protein-energy malnutrition and moderate to high levels of infectious disease. These children may parallel those from the past, whose remains are studied by skeletal biologists or paleoanthropologists. Our findings reinforce concerns expressed in extant studies regarding the accuracy of age-at-death reconstructions.

The process of growth and development represents one of the crucial interfaces between biology and the environment, and thus studies of children may yield answers to many questions of interest to physical anthropologists. Research on children has been undertaken to determine the contribution that growth processes may make to differences in adult morphology; children's growth is a traditional marker of population health; and relative growth rates have been used in debates concerning the origins of modern human childhood. Studies of deceased ("past") populations may explore these or other issues. The latter include analyses of immature specimens to establish the demographic profile of a population. All such studies rely on age-at-death assessments of juvenile skeletal remains.

When one seeks understanding of the biology and lifeways of past populations, the study of immature specimens must be based on the knowledge gained from the examination of living children. However, aspects of the growth process of living children contribute to difficulties involved in the study of juvenile skeletal and dental remains. Saunders' (1992) review demonstrates that problems arising from variability in the living are often recognized in studies of ossuaries and a variety of other group or cemetery recoveries. However, appreciation of significant variability in human growth and maturation rates is less common in studies of early hominid juveniles (Lampl et al., 1993).

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Because the problems are similar, regardless of provenance and geological age of the specimens, our study applies equally to analytical problems in the investigation of recent and more ancient juvenile hard tissue remains. To signify this commonality, we employ the descriptor *skeletal juveniles* in this paper, by which we mean subadults studied by both skeletal biologists and paleoanthropologists.

Our present research addressed the following issues. While variability is to be expected in the growth rates of individuals who were members of deceased populations, the extent of this variability between maturational and chronological ages is unknown. This is a significant research concern for any study that aims to age skeletal juveniles and to employ these data in a meaningful context. The ages at death are estimated in immature skeletons by determination of the maturational stages of the available bones and teeth. A number of researchers note that their chronological age estimators are, in fact, bone or dental age assessments, but none can state how much variation between chronological and maturational age may actually occur in skeletal samples. Furthermore, assessments of bone and dental age are based on a chronological age-based maturational status reference standard in a current population, which may or may not be appropriate for the skeletal group under investigation.

Two primary sources of error occur in all estimates of age in skeletal juveniles obtained by the use of standards derived from the living. The first is often considered to be random error: within a population, there is variability between children of the same age in their levels of maturation (reviewed in Eveleth and Tanner, 1976, 1990). This yields the common observation that, for example, some 4-year-olds have more teeth than others. The second is systematic error, which is produced by shared environmental circumstances that result in children of a local population being relatively similarly delayed or advanced by reference to a standard of known chronological age (Eveleth and Tanner, 1976, 1990).

In general, three issues summarize problematic methodological aspects of research on the growth and development of skeletal children in the literature: sampling, estimations of age at death, and the appropriate use of reference standards for these assessments.

SAMPLING

Developmental reconstructions of skeletal juveniles often face serious problems of sampling. These obstacles are discussed here.

Fragmentary nature of remains prior to deliberate interment

In cases like that of the Gibraltar neandertal child, controversy surrounding taxonomic growth patterns arises from the question whether one or two individuals are represented by the remains (Tillier, 1988; Dean et al., 1986). In general, difficulties in understanding juvenile growth patterns are increased in palenotological samples because materials are quite fragmentary and rare. Taxonomic groupings of, for instance, juvenile specimens of *Australopithecus africanus,* found at three sites separated by hundreds of kilometers and perhaps hundreds of thousands of years in time, are by necessity analyzed together as a sample. Nevertheless, it is difficult to propose a growth pattern for the taxon based on maturation-based chronological aging of such remains in light of the practical issues of developmental variability, however it was expressed in the taxon. Certainly, for specimens either not interred or ones that have suffered postmortem disturbance, problems of skeletal association of individuals complicates interpretations of age and relative developmental status.

Limitations in the developmental age span of remains

Even when the sample derives from relatively recent burials, serious problems in understanding growth throughout the developmental period are posed by the ages at which children actually died. For example, the Spitalfields sample, a rare collection of children of known age, had a relative dearth of specimens from middle childhood (Molleson et al., 1993). How children grew during this developmental period remains enigmatic even in this superb sample.

Morbidity and mortality patterns

Infants and children who comprise skeletal samples are those who died and may or may not reflect growth processes followed by their contemporaries who survived (as discussed by Saunders and Hoppa, 1993).

AGE AT DEATH

A serious problem in reconstructing the growth patterns of the children of any skeletal sample concerns accuracy of aging. The assessment of the age at death is necessarily based on the determination of a skeletal or dental age, which is based on a comparison of the maturational state of the remains with a chronological age–based reference standard. Because the ages at death of immature skeletons are estimated by determining the maturation stages of the available bones and teeth, the investigator obtains not a true chronological age but rather a skeletal or bone age (if sufficient skeletal remains exist) or, more commonly, a dental age.

REFERENCE STANDARDS

A skeletal or dental maturational age represents the level of skeletal development as determined by epiphyseal union and the level of dental development as determined by calcification, root development, and eruption status, attained by children of a known chronological age in what is a standard or reference population. This is a somewhat spurious task at best, as established growth reference standards are simply descriptive statistics applied to groups of children and these are appropriately used only for assessing clinical normality of children within the population, not for the aging of other, unrelated individuals (Tanner, 1986).

Reference standards presently available derive primarily from Western European samples and reflect individuals who are relatively healthy in their particular ecological context. While the use of several different population's standards has been suggested as a means of circumventing population-specific maturational differences in the analysis of skeletal juveniles, most presently available standards do not accurately reflect in their distribution functions the discrepancy in maturational and chronological ages common in populations systematically subjected to environmental hardship.

It is important to point out that growth is itself a longitudinal process whereby changes occur through time, and any accurate understanding of how children proceed through this process must be based on longitudinal studies, following the same children through development. Research aiming to reconstruct how human growth occurred in past populations by reference to the remains of limited samples of deceased children suffers from data that are basically cross-sectional. That is, each specimen represents one moment in the life span of that individual, and each contributes to a population pattern in the same way that a one-time measurement on a living child would contribute to an understanding of how children in one population grow through time. Indeed, the reconstruction of growth patterns of skeletal juveniles is by necessity a cross-sectional study in which the attempted reconstruction of growth patterns is based on a different individual(s) at each age. Thus, determining how much variability might be expected to be found between maturational and chronological age has most important implications for studies whose data base is heavily dependent on the ages of skeletal juvenile specimens.

In order to illustrate some of the problems inherent in assigning chronological ages based on the maturational status of individuals, we have compared the skeletal and dental maturation of several samples of living children of known age and sex. These data aim to provide a perspective on the magnitude of potential error involved in the aging of skeletal children.

MATERIALS AND METHODS

Present skeletal sample

The sample of children of known chronological age used for skeletal age analysis derives from a population in Mexico, removed from modern Western medical care, with a high level of infectious disease and chronic mild to moderate protein-energy malnutrition. These data were collected as part of a larger study of the ecology of malnutrition

and have been previously described in a number of publications (e.g., Cravioto et al., 1969; Johnston et al., 1980a,b, 1984). These children do not represent a population in extremis but serve as a reference sample for many ecologically diverse samples prior to modernization.

This sample has not been chosen as representative of any population or geographical region. Rather, it is seen as representative of groups living under conditions of relative environmental stress, not unlike those whose remains are studied by anthropologists working with earlier populations. In particular, this sample can reveal the range of variability likely to be encountered among samples of children whose growth is constrained by their environments. Specifically, these children comprise a 1-year birth cohort of a rural community in southern Mexico, followed from birth through age 7. A complete description of the community, the study design, and the first month's findings are given by Cravioto et al. (1969). Analyses of growth, morbidity, and skeletal maturation have been presented by Condon-Paolini et al. (1977) and Johnston et al. (1984), and the relationships of growth variation to environmental factors may be seen in Johnston et al. (1980a,b). Comparisons to reference data show clearly that these children are characterized by widespread growth faltering and significant delay in their rates of biological maturation (described below).

In the present study, we are interested in identifying the variability in skeletal ages in this sample of children of known chronological age and sex. The skeletal ages of the children were assigned from the bones of the hand and wrist employing radiographs of the left hand, using the Greulich-Pyle method[1] (Greulich and Pyle, 1959).

Three subsamples were employed in the present report: 183 children examined within 2 weeks of the sixth birthday, 217 children examined between 4.0 and 4.5 years of age, and 130 children who were assigned a skeletal age of 39–44 months.

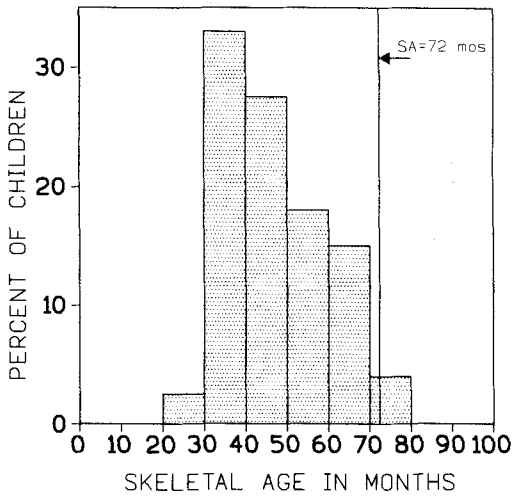

Fig. 1. Frequency distribution of the skeletal ages (SA) (in months) for 183 Mexican children of the same chronological age (72 months ± 1 week). If skeletal ages accurately aged these children, the distribution would be centered on the vertical line at 72 months. By contrast, the distribution of skeletal ages in these children is significantly skewed to the left. Thus, in general, children in this sample are significantly under-aged according to their chronological age by employing hand-wrist skeletal aging criteria (Greulich and Pyle, 1959). The standard deviation of skeletal ages was 11.91 months, the 95% confidence interval of chronological age vs. skeletal maturation is 4–8 years, and, thus, the error in assigning chronological age at death to any individual has a 95% confidence interval of ±2 years.

Dental sample

It has often been said that skeletal growth and maturation is more affected by systematic factors than is the development of the dentition, and thus dental ages are preferable to skeletal ages in the attempt to assign correct chronological ages. In order to investigate primarily random error or the contribution of variability in individual maturational timing on errors of dental aging, we have employed data published by Demirjian (1978, 1979) on a sample of healthy French-Canadian children (a total of 2,047 boys and 2,349 girls, 2–20 years of age) examined at the University of Montreal Growth Centre.

The published data are presented as centile curves of dental maturity scores based on a maturity scoring system developed by Demirjian and colleagues (Demirjian et al.,

[1]The hand-wrist films were read by T. Scholl as part of a larger investigation.

1973). Because these data were collected on children of known age, the published standards can be referenced to ascertain the range of maturational ages at any chronological age. For example, the percentile chart for dental age (as published in Demirjian, 1978, 1979), can be used to locate the third and ninety-seventh percentile dental scores for chronological age. These scores can then be converted to dental age by reference to the published table of maturity score/dental age conversion (Demirjian et al., 1973), and a probability statement regarding the age range in this population for an age/maturity score can be ascertained (Demirjian, personal communication).

RESULTS

Skeletal age vs. chronological age

Skeletal age variability at 6 years of age. The individual variability in skeletal ages of 183 children of the same chronological age (6 years ± 1 week) is illustrated in Figure 1 as a distribution of skeletal ages. In this sample, the 95% confidence interval of a chronological age based on this level of skeletal maturation is 4–8 years. The standard deviation of skeletal ages was 11.91 months, and the error in assigning chronological age at death to any individual would have a 95% confidence interval of plus or minus 2 years.

It is notable, furthermore, that the distribution of skeletal ages in these children is not random or Gaussian but is significantly skewed to the left. Thus, in general, the effect of the application of this skeletal reference is to significantly underage these children by comparison with their actual chronological ages.

Errors in chronological age assessment based on skeletal aging. The relationship between chronological and skeletal aging is further illustrated in 217 children between 4.0 and 4.5 chronological years of age from the same sample. Figure 2 presents the deviation of skeletal age from chronological age in terms of years of delay from actual chronological age. Underaging is again evident: If skeletal development–based ages were to be used as an indicator of chronological age, the following errors would result: 60% of this sample would be underaged by 1–2 years and more than 20% of the sample would be underaged by 2–3 years. These aging errors represent some 25%–75% of the actual ages of the children.

Chronological age variability at skeletal ages between 39 and 44 months. The 130 children who were assigned a skeletal age of 39–44 months serve to illustrate the distribution of actual chronological ages of a group of children who were comparable in terms of skeletal ages (Fig. 3). In this sample of children of essentially the same level of skeletal development for their sex, their actual chronological ages span a range of 41 months, from 48–89 months of age. This actual age range distribution encompasses a 100% variability in the actual age by comparison with the derived skeletal age. Notably, chronological ages are underestimated in these children in every case.

The specific distribution of errors from the skeletal maturity assignment, in terms of months of difference between skeletal age and chronological age, is most informative (Fig. 4). The errors in aging are, again, not Gaussian; in fact, large errors are as common, if not more so, than small ones. As shown in Table 1, only 13% of the children are aged within 1 year of their actual chronological age, and less than half of the sample is aged within 2 years of their actual age. In fact, 22% of this sample is characterized by up to 4 years of error in assignment. In view of the fact that this group of children is aged skeletally between 3.25 and 3.7 years of age, a 4 year mistake in age assignment is a tremendous error factor.

Dental age vs. chronological age

A parallel issue concerns the error in chronological age estimation based solely on dental aging. Table 2 documents the ranges of dental age at any single chronological age between 4 and 10 years from the sample of Demirjian (1978, 1979). The healthy children in this sample exhibit significant variability in their maturational rates. For example, 94% of normal girls of chronological age 6 years range in dental ages between 4.75 and 7.5 years, and 94% of boys at 6 chronological years of age range in dental

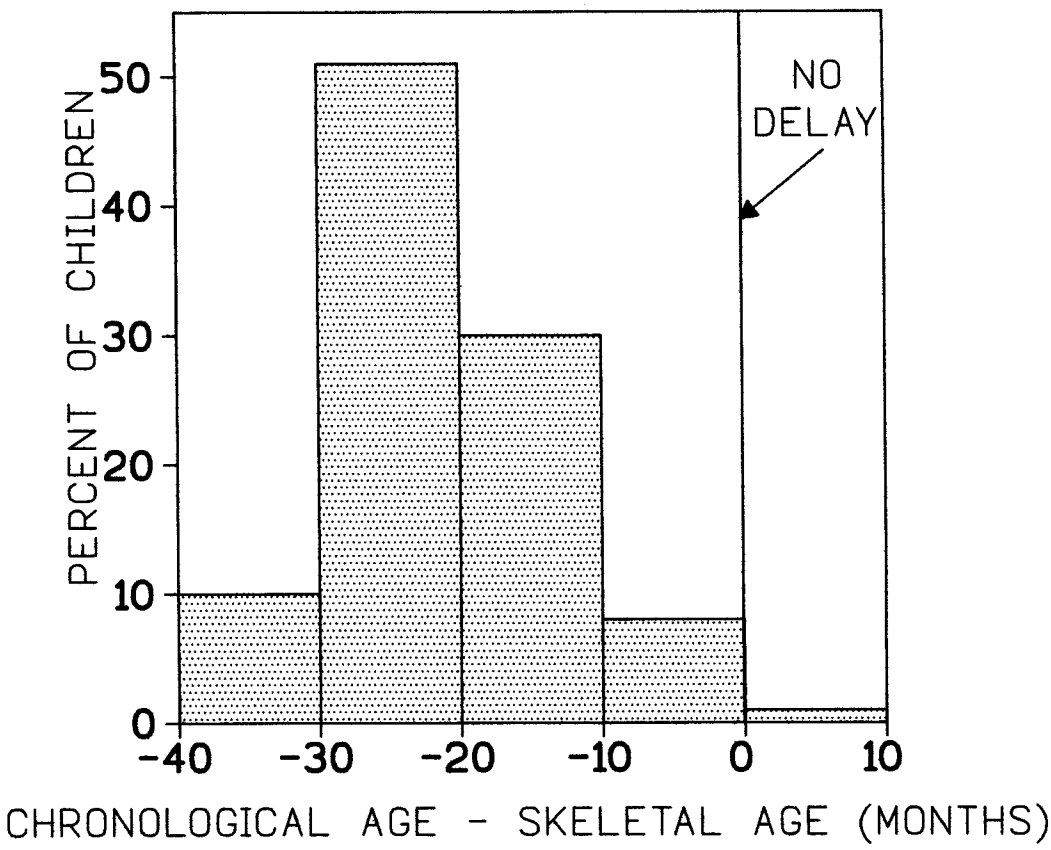

Fig. 2. Skeletal age compared to chronological age in 217 rural Mexican children examined between 4.0 and 4.5 years of age (children from the same sample as Fig. 1). The deviation of skeletal age (SA) from chronological age (CA) is shown in terms of months of delay in skeletal age from actual chronological age (chronological age minus skeletal age). If skeletal development were used as an indicator of chronological age, 60% of this sample would be underaged by 1–2 years and more than 20% by 2–3 years.

age between 5.95 and 7.55 years. Thus, children who are actually 6 years of age chronologically span nearly 3 years of variability in maturational age (4.75–7.5 years), or more than half of their actual age.

Table 3 addresses the questions of variability in chronological age at any single maturational stage of the dentition. For example, at maturity score 33, the fiftieth percentile for children of chronological age 5 years, 94% of the children in this sample were of chronological ages ranging from 3.3–6.8 years. Thus, any single individual with this particular combination of developing teeth cannot be given a single age assignation but can accurately only be assigned a probability estimate within this 3.5 year age range. In the absence of documentation regarding chronological age, one must state that a radiograph of this dental configuration represents with 94% probability an individual from this population between 3.3 and 6.8 years of age.

DISCUSSION

These data document the importance of considering both individual biological variability in maturation rate and systematic environmental effects on growth and maturation in studies based on assignation of age at death to skeletal juveniles. Individual developmental variability and systematic environmental effects added to genetic factors have been shown to influence significantly

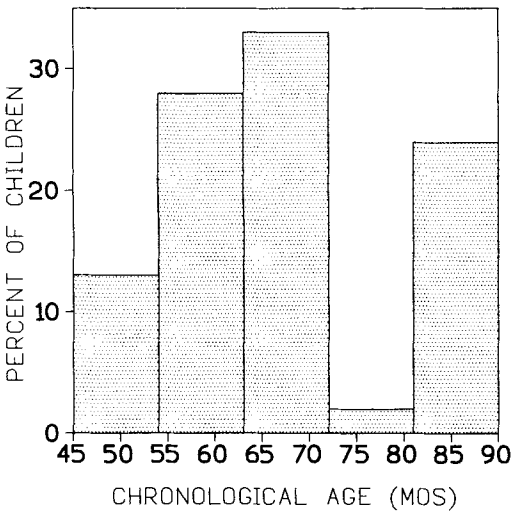

Fig. 3. Distribution of the chronological ages of 130 Mexican children at skeletal ages of 39–44 months (Greulich and Pyle, 1959). This histogram illustrates the distribution of the actual chronological ages of individuals with comparable skeletal ages. A chronological age span of 4–7.5 years is represented by skeletal maturity ages between 3.25 and 3.7 years.

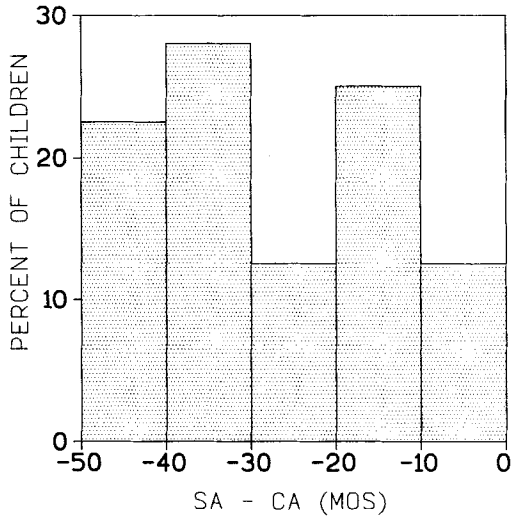

Fig. 4. Distribution of age-assignment errors. The distribution of errors from such an assignment, in terms of months difference between skeletal age and chronological age, demonstrates a non-Gaussian distribution in which large errors are as common, if not more so, than small ones. Chronological age is underestimated in every case. As further documented in Table 1, only 13% of the children are aged within 1 year of their actual chronological age, and less than half of the sample is within 2 years of their actual age. Of this sample, 22% is characterized by up to 4 year's error in age assignment.

the rate of skeletal and dental maturation in the samples we have examined. These effects are present in two healthy populations as part of the variability in individual growth processes (shown here by the dental development of healthy Canadian children) and are particularly likely to be evident in populations exposed to adverse environments (illustrated here with the data from the Mexican sample). In well-nourished societies, a given level of skeletal maturation may be associated with a chronological age of 5 years, while in a population where there is malnutrition, children may not attain the same level until 7 chronological years. Since our reference standards are developed from populations free of nutritional deficiencies and high prevalence of disease, the ages at death of children in many skeletal samples may be significantly underestimated. Many researchers are well aware of this point, and we aim only to add a perspective on the range of variability that this may actually reflect.

We do not imply that hand-wrist assessments are commonly used in skeletal samples which must rely on estimates of maturational stages of available remains, them-

TABLE 1. Distribution of age-assignment errors of 130 Mexican children of skeletal age 39–44 months

Error (months)	Frequency	Percent	Cumulative frequency
−4 to −11	17	13.08	13.08
−12 to −23	37	28.46	41.54
−24 to −35	47	36.15	77.69
−36 to −47	28	21.54	99.23
−48 to −50	1	0.77	100
Total	130	100	

TABLE 2. Third to ninety-seventh percentile ranges of dental ages at annual chronological ages by reference to the data from healthy Montreal children[1]

Chronological age	Dental age ranges	
	Males	Females
4	<3.0–6.4	<3.0–6.3
5	3.7–7.1	3.4–7.05
6	5.95–7.55	4.75–7.5
7	6.2–8.1	6.2–8.1
8	7.1–9.2	7.2–9.0
9	7.7–11.0	7.7–10.4
10	8.2–12.6	8.1–12.7

[1] Source: Demirjian, 1978, 1979; Demirjian et al., 1973.

TABLE 3. The ranges (3–97%) of chronological ages (CA) at single maturational dental stages[1]

	Males		Females	
CA	Maturity score[2]	CA range (years)	Maturity score	CA range (years)
4	24	2.0–5.9	24	2.3–5.8
5	33	3.3–6.8	33	3.3–6.5
6	42	4.2–7.5	44	4.3–7.3
7	53	5.5–8.3	60	5.5–8.3
8	71	6.8–9.6	77	6.9–9.8
9	83	7.6–10.8	85	7.5–10.8
10	88	8.8–12.0	92	8.8–11.8

[1] The CA ranges represent actual ages at which 94% of the sample experience a maturity (MS) assigned to a developing dentition according to the method of Demirjian et al. (1973).
[2] Here the fiftieth percentile maturity scores (MS) at annual chronological ages (CA) are employed to illustrate the ranges in actual chronological ages (CA range) in children with these combinations of developing teeth. Data are from healthy Montreal children (Demirjian, 1978, 1979).

selves often fragmentary. However, this analysis provides a perspective on the relative reliability one can expect when employing reference standards developed on healthy American children to samples of diverse ethnic and environmental backgrounds. Such work is necessarily common in skeletal biology (e.g., Lovejoy et al., 1990; Merchant and Ubelaker, 1977). Through no error on the part of the researchers but because of the limitations of the existing comparative standards, investigators are restricted in their age interpretations by the lack of data documenting variability in maturational rates. The present data provide some perspective on the magnitude of this problem.

The samples presented here are expected to be reasonable proxies for any number of past populations. We emphasize that these samples are not worse case scenarios but represent relatively healthy children who reside in ecologies at risk for nutritionally based and infectious disease–related patterns of growth and development without medical interventions.

The skeletal age data reported here were estimated by the Greulich-Pyle (GP) method (Greulich and Pyle, 1959). The children forming the source of this reference are of northwestern European origin living in middle class America during the 1950s, and it is expected that the maturity ratings using this reference would under-age the present sample of children. In a comparison with the Tanner Whitehouse system (TW2), Tanner et al. (1983) point out that the GP system emphasizes maturity differences between the American-based growth patterns and the English-based sample underlying the TW2 system after 6 years of age by some 6–9 months due to the slower maturation of the British children. In general, they point out that the rate of skeletal maturation in populations differs in both the mean skeletal maturity at any given age and the patterns of increments from age to age. Neither the GP nor the TW2 system, the two major resources for estimating skeletal maturity, is drawn from samples like the present one, and thus a comparison with both will well demonstrate environmental and genetic differences that can occur in the age-based maturation of the skeleton.

It is of interest that the GP reference sample parallels the children who form the basis of a dental reference standard commonly employed in a number of recent skeletal studies (Moorrees et al., 1963). For example, Saunders et al. (1993) employ the Moorrees et al. (1963) standards on a sample of children from a nineteenth-century Canadian cemetery. A series of 17 identified individuals of known age at death were available for analysis: seven below 1.5 years of age, seven between 2 and 4.1 years of age, and two approximately 8 years old. While not faring badly in aging the specimens under 2 years of age, the reference standards generally underaged the sample specimens who were over 3 years of age. For the child of 8.42 years, the dental age according to the Moorrees et al. reference standards was 6.28, underaging the child by 25% of the actual age. The Canadian specimens were of European origin, and thus the application of European-

based reference standards was warranted. Even in this case, significant error is evident.

While it is commonly assumed that the dentition is less effected by environmental factors than the skeleton during development, the background variability in a relatively homogenous and healthy sample such as that employed here should be a serious caution against assumptions that mean values are universally applicable. While no doubt there are individuals whose dental remains will be accurately assessed employing reference standards (Smith, [1991] identified four individuals), the assumption that this implies accuracy of mean dental ages in assessing individuals from diverse populations would be unwarranted. The results from the present dental analysis point out the substantial variability within a healthy Canadian population in ages of attainment of dental maturation stages and thus emphasize the caution we believe is necessary in aging analyses, including those based on the dentition.

Our observations of under-aging based on maturity indicators from reference populations in the Mexican sample merit discussion. We would predict this same problem to occur in skeletal samples derived from similar environmental backgrounds—that is, those that represent life styles in which nutrition and disease are direct contributions to child growth in the relative absence of medical care. Clearly, it is not possible to identify the presence of such factors in all skeletal samples. The scholarly issue is that these unknown environmental factors cannot be excluded from consideration in the aging of unknown specimens. We reiterate that the children in our Mexican sample were generally healthy children, albeit constrained in their maturational progress.

It is notable that in some of the rare studies of skeletal samples in which there are children of known age, comparisons between maturational and chronological ages describe findings similar to those we report here. For example, in the Spitalfields sample of children with documented ages at death (Molleson et al., 1993), it is observed that both dental and long bone growth retardation are evident in practically all children aged over 1 year. Molleson et al. (1993) obtain these results by comparison of the Spitalfields skeletal specimens with the dental standards of Schour and Massler (1941) and the long bone references published by Maresh (1955) (cited in Molleson et al., 1993). While some of this apparent stunting in long bone growth may reflect the nature of the growth standards used for comparison, the individual variability in dental maturational rates in the sample children is considerable. Chronological ages of individuals at dental stage 7 (according to Schour and Massler [1941], used by Molleson et al. [1993] as noted above) ranged from 2.5–5 years and by stage 17 included individuals of chronological ages 13–19 (Molleson et al., 1993).

A study of maturational variability in living children complements studies of skeletal populations and provides a perspective that echoes the observations of a number of previous skeletal researchers cautioning investigators in the validity of age prediction assessments of skeletal juveniles due to both inherent errors in aging and population-specific growth profiles evident in skeletal samples themselves (Hoppa, 1992; Merchant and Ubelaker, 1977; Ubelaker, 1984, 1987). Previous investigations aiming to document the range of this problem in modern human samples of known age have been primarily directed towards pathology room specimens of older ages (e.g., Webb and Suchey, 1985) rather than young, demographically homogenous samples.

The data presented here illustrate 95% confidence intervals significantly broader than is assumed to be the case in some recent publications (Miles and Bulman, 1994) and strongly support the use of statistical probability ranges in assigning ages at death. While this may not be as convenient in reconstructions aiming to provide longitudinal perspectives on the patterns of child growth in past populations, it is a necessity for the attainment due to the nature of the biological process of growth.

Researchers who focus on the growth and maturation of living children have at their disposal basic information, such as chronological age, that paleoauxologists (Tillier, 1995) do not. The present data aim to contribute a perspective to studies that strive

to reconstruct growth patterns based on skeletal individuals, whose age at death determinations form the basis for controversial aspects of human evolution and biology.

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